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Performance and Costs of Particle Air Filtration in HVAC Supply Airstreams

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Abstract

This paper uses a model, and data on particle size distributions, filter efficiencies, and particle deposition rates to estimate the reductions in the indoor mass concentrations of particles attainable from use of filters in HVAC supply airstreams. Additionally, the energy and total costs of the filtration options are estimated. Predicted reductions in cat and dust-mite allergen concentrations range from 20% to 60%. Increasing filter efficiencies above approximately ASHRAE Dust Spot 65% (MERV 11) does not significantly reduce predicted indoor concentrations of these allergens. For environmental tobacco smoke particles and outdoor fine mode particles, calculations indicate that relatively large, e.g., 80%, decreases in indoor concentrations are attainable with practical filter efficiencies. Increasing the filter efficiency above ASHRAE Dust Spot 85% (MERV 13) results in only modest incremental decreases in concentrations. Energy costs and total costs do not always increase for higher efficiency filters. Total estimated filtration costs of \$0.70 to \$1.80 per person per month are insignificant relative to salaries, rent, or health insurance costs.

Introduction

Several classes of health effects are linked to particle exposures that may be reduced via filtration. Allergy and asthma symptoms may be produced in susceptible individuals upon inhalation of allergenic particles, such as pet allergens, dust mite allergens, and pollen from outdoor plants (Committee on Health Effects of Indoor Allergens 1993). Infectious diseases such as influenza and some common colds can result from the inhalation of droplet nuclei from people's coughs and sneezes that carry infectious organisms (e.g., Dick et al. 1987). Environmental tobacco smoke (ETS), a mixture of particles and gases, is associated with increases in lung cancer, heart disease, asthma exacerbation, and other health effects (e.g., California EPA 1997). Increased concentrations of particles in outdoor air are associated with increases in hospital admissions, deaths, and other health effects (EPA 1996a); however, most people's exposures to these outdoor particles occur predominately indoors where approximately 90% of their time is spent. The sizes of the particles linked with health effects vary widely. Since filter efficiency and rates of particle deposition to surfaces also vary with particle size, the concentration reductions attained from filtration, and the incremental benefits of using higher efficiency filters, will vary markedly with particle type. Despite the widespread use of filtration systems, the influence of different air filtration options on indoor concentrations of particles has not been well documented.

Methods

Reductions in indoor concentrations

A mass-balance model was used to estimate the reductions in the indoor concentrations of different particle types from use of air filters in supply airstreams of HVAC systems. The modeling assumes a

well-mixed indoor space and integrates over particle size, accounting for the size distributions of source-specific particles and the size-dependent variations in both filter performance and particle deposition losses to surfaces. The modeling also accounts for particle entry via infiltrating outdoor air that does not pass through the filters in the HVAC system. The percentage reduction in indoor particle mass concentration was used as the performance metric, with the reference case typically being no filter. A detailed description of the model and the model input parameters is provided in Fisk et al. (2002).

Calculations were performed for non-reacting outdoor fine-mode particles (smaller than $3.1\ \mu\text{m}$) and for three types of indoor-generated particles – those with dust mite allergen, with cat allergen, and from environmental tobacco smoke (ETS). Our calculations do not apply for the many gaseous compounds within ETS, which will not be removed by particle filters. The detailed particle size distribution data used in the calculations are provided in Fisk et al (2002). For cat allergen, 60% to 70% of the mass is within particles larger than $5\ \mu\text{m}$ in aerodynamic diameter. For dust mite allergen, 80% to 90% of the allergen mass is in particles larger than $4\ \mu\text{m}$. ETS and outdoor fine mode particles are much smaller. Approximately 97% of the mass of ETS particles is within particles smaller than $1\ \mu\text{m}$ and approximately 93% of the mass of outdoor fine mode particles is in particles smaller than $1\ \mu\text{m}$ in aerodynamic diameter.

As an overall (i.e., single-number) efficiency rating, we have characterized filters according to the ASHRAE Dust Spot Efficiency Rating (ASHRAE 1992), the standard rating used until recently by U.S. industry. To denote the ASHRAE Dust Spot Efficiency, we will use the notation “ASHRAE nn%” where “nn” refers to the Dust Spot Efficiency rating. In parenthesis, we provide the corresponding MERV filter efficiency rating, based on ASHRAE’s new filter testing standard. There is no unique filter efficiency curve, i.e., curve of particle removal efficiency versus particle size, for each Dust Spot Efficiency Rating; hence, we have performed calculations with example efficiency curves based on data provided by Hanley et al. (1994) and provided by manufacturers. For some filters, we extrapolated from the reported data to estimate filter efficiency for the largest particles. These example efficiency curves are provided in Figure 1. To maintain readability, we have not shown the curve for high efficiency particulate air (HEPA) filters which have a rated minimum efficiency of 99.997%.

We neglected air bypass, which is the leakage of air between adjacent filters and between filters and the framework holding the filter. Insufficient information is available on typical rates of bypass, although the limited information available indicates that bypass rates will often exceed 10%. By neglecting bypass, we overestimate the particle removal efficiencies of the filtration systems. However, we have also used the particle removal efficiencies of new filters, and efficiency normally increases as filters load. This simplification causes an underestimation of time average particle removal efficiencies.

We assumed that the rates of outside airflow and recirculation airflow were one and four indoor volumes per hour respectively (denoted by $1\ \text{h}^{-1}$ and $4\ \text{h}^{-1}$). Most calculations assumed an air infiltration rate of $0.25\ \text{h}^{-1}$. For some calculations, we assumed no infiltration or no recirculation.

Costs of Air Filtration

The detailed method used to calculate costs is provided in Fisk et al. (2002). As background for the filtration cost calculation, we note that filters vary a great deal in the degree of pleating (i.e., folding of the filtration media) and in the depth in direction of airflow. Depth may vary from approximately 2 cm to 30 cm (1 to 12 inch). With an increase in depth and pleating, the area of filtration media increases, price usually increases, and the ratio of pressure drop to efficiency usually decreases. To limit pressure drops, more efficient filters tend to have increased pleating and depth. Because of their increased surface area, these larger filters will often have an increased lifetime before excessive pressure drops make it necessary to replace the filter.

The total costs of different air filtration options per unit of filtered airflow were estimated, accounting for the costs of periodically replacing the filters (materials plus labor) and the incremental costs of energy used by fans. Since products with a similar particle removal performance can vary in price and airflow resistance (which affects energy costs), our estimates are examples that serve only to illustrate approximate costs and their variability among the filtration options.

The costs of a variety of filters were provided by vendors. Limited information was available for estimating the costs of labor for periodic filter replacement (removing old filters and installing new ones). The standard handbook for estimating labor time required for facilities management (RS Means 1999) does not provide different time estimates for filters with different efficiency ratings and allocates only 0.078 labor-hours for filter replacement in air handling systems that would typically have 3 to 8 filters, corresponding to 0.6 to 1.6 minutes of labor per filter. With the total labor cost of \$46 per hour (RS Means 1999), including overhead and profit, the cost per filter installation is only \$0.5 to \$1.2. However, based on our experience, filter installation labor and costs will often be higher than these estimates. For example, documentation from the U.S. Department of Defense (DOD 1987) estimates 0.07 labor-hours (4.2 minutes) per filter for removal and replacement. In addition, we believe that installation labor and costs will increase with filter efficiency because more efficient air filters are larger and heavier, and sometimes have more complex installation hardware. Consequently, calculations reported in this paper used the following assumed installation labor cost schedule: \$3 (4 min.) per filter for filters with a depth in the direction of airflow ≤ 4 inch (10.2 cm); \$5 (6.5 min.) per filter for filters with a depth of 6 inch (15.2 cm), and \$10 (13 min.) per filter for filters with a depth ≥ 12 inch (30.5 cm). For total cost estimates using a labor cost that does not vary with filter size or efficiency, see Fisk et al. (2002)

The filter lifetime was estimated based on the published dust holding capacity, arrestance efficiency rating (ASHRAE 1992), manufacturer's recommended maximum pressure drop, and rate of airflow as described in Fisk et al (2002). We assumed that air flowed through the filters 12 hours per day and six days per week. For the inlet particle concentration, we used the arithmetic average of the indoor and outdoor daytime PM10 concentration (i.e., mass concentrations of particles smaller than 10 μm aerodynamic diameter) from a survey of 28 U.S. office buildings ($22 \mu\text{g m}^{-3}$).

The filtration energy cost was computed as the product of the fan power needed to force the air through the filters, fan operating time, and assumed electricity price (\$0.10 per kWh). The fan power was estimated using standard fan laws (ASHRAE 1996); however, changes in fan power with pressure drop will vary with the type of fan and associated flow control system. Values of 0.9 and 0.75 were used for the motor efficiency and fan efficiency, respectively. These values are representative of the performance of motors and fans in large commercial building HVAC systems. Smaller systems will often have less efficient motors and fans.

Results

Figure 2 shows the predicted reductions in indoor concentrations of cat and dust mite allergen and ETS particles from use of six filters in supply airstreams, ranging from an ASHRAE 20% filter (MERV 6 or 7) to a HEPA filter. For cat and dust-mite allergen, which is predominately found in particles with a diameter of several micrometers, the predicted reductions in indoor mass concentrations (mass per unit air volume) range from approximately 20% to 60%. For these allergens, data on particle size distribution is sparse and the predicted concentration reductions obtained using two different sets of particle size data differ substantially. Increasing filter efficiencies above approximately ASHRAE 65% (or possibly 85%) [MERV 11 (or 13)] does not reduce indoor concentrations of cat and dust-mite allergen significantly because even moderate efficiency filters work well for the larger diameter particles containing most of the cat and dust-mite allergen.

For environmental tobacco smoke particles, which are almost entirely submicron in size, the predicted indoor concentration reductions from use of low to moderate efficiency filters [ASHRAE 30% and 45% (MERV 7 to 9)] are very small (5% to 12%). Increasing the filter efficiency to ASHRAE 85% (MERV 13) yields a predicted concentration reduction of 61%. Further increases in filter efficiency bring modest additional benefits, up to a 75% reduction in concentration with use of a HEPA filter.

Figure 3 shows the predicted reductions in outdoor fine-mode particles. The predicted benefits of low to moderate efficiency filters, ASHRAE 45% (MERV 9) and lower, are again quite small. The reduction in concentrations from a filter with an ASHRAE 85% rating (MERV 13) is 80% with base-case assumptions (1 h^{-1} of mechanical outside air ventilation, 0.25 h^{-1} of unfiltered infiltration, and 4 h^{-1} of recirculation). Upgrading to a HEPA filter brings only a modest additional benefit, with a predicted reduction in concentration of 95%. If there is no infiltration, the predicted reductions in indoor concentration are two to six percentage points higher. If the building does not recirculate air, the concentration reductions are significantly smaller and the benefits of increasing filter efficiency above ASHRAE 85% (MERV 13) are more pronounced.

Figure 4 displays the predicted energy and total costs of using ASHRAE 25% to ASHRAE 95% (MERV 7 to 14) filters in HVAC supply airstreams. Costs are provided per 1000 ft^3/min (470 L/s) of filtered supply air, which would typically serve 5–7 persons in a U.S.-style office building with air recirculation or 10 to 15 occupants in European buildings without air recirculation. Monthly energy costs range from \$3.26 for a filter with an efficiency rating of 30% (MERV 7) to \$5.94 for a filter with an efficiency of 95% (MERV 14). With the labor cost schedule for filter replacement, total monthly costs range from \$3.90 to \$11.10. There is a general tendency toward higher energy and total costs with higher efficiency filters; however, the costs of using different filter products of the same efficiency vary widely. Consequently, use of more efficient air filters does not always increase costs. For example, monthly costs per 470 L/s (1000 ft^3/min) of filtered supply air were as high as \$5.60 for a 25% filter efficiency (MERV 7) and as low as \$4.20 for a filter with a 60% efficiency (MERV 11).

The costs displayed on Figure 3 are based on the manufacturers' rated air flows and average of the initial and recommended final pressure drops for the filters. With the assumed inlet particle concentrations and hours of usage, the predicted filter lifetimes range from two to 27 months. Energy consumption and energy costs will be smaller if the filter is replaced with a smaller final pressure drop; however, the costs of purchasing filters and the labor for filter replacement will increase. Using the data available from one major filter manufacturer, a limited sensitivity analyses explored the trends in total life cycle cost as final pressure drops decreased from the manufacturer's recommended values. In general, total predicted monthly costs increased or decreased less than 10% as the final pressure drop at filter replacement was decreased by up to 0.4 inch of water (100 Pa). In a few cases, total monthly costs decreased by 30%. Consequently, more frequent filter replacement could save energy and sometimes also slightly decrease filtration costs.

Discussion

Filter selection and costs

Two results of this modeling may be surprising to some readers. First, since filters are more efficient in removing larger particles from airstreams, one might expect filtration to decrease indoor concentrations of cat and dust mite allergens by a larger percentage than concentrations of ETS and outdoor fine mode particles. Except for the lowest efficiency filters, the findings are inconsistent with this expectation. The large losses of the large allergen particles by deposition on indoor surfaces are the explanation. Because these allergen particles are removed from indoor air at a substantial rate by deposition on surfaces, the filtration increases the total particle removal rate by only a moderate percentage. The rates of loss of the

much smaller ETS and outdoor fine mode particles by deposition on surfaces are much smaller; thus, filtration can increase the total particle removal rates by a larger percentage.

Readers may also be surprised by the relatively small, and in some cases totally negligible, incremental benefits of using the highest efficiency filters. However, Figure 1 shows that an ASHRAE 65% filter (MERV 11), an ASHRAE 95% filter (MERV 14), and a HEPA filter have a nearly identical and very high efficiency for particles larger than 3 μm in aerodynamic diameter. Thus, when much of the particle mass is predominately composed of large particles, the filters with a higher efficiency rating are not much more effective in particle removal.

Anecdotally, building engineers and operators often report that high efficiency filters in the supply airstreams of HVAC systems have an excessive airflow resistance, consume too much energy, and are prohibitively expensive. However, our analyses do not support such reports for filter efficiencies up to ASHRAE 90% (MERV 14). The average of the initial and recommended-final pressure drops does not necessarily increase significantly with a higher efficiency rating (results not shown). For example, the average pressure drop of four ASHRAE 30% filters (MERV 7 or 8) was about 0.64 inch of water (160 Pa), while three out of six ASHRAE 90% filters (MERV 13 or 14) had very similar average pressure drops of approximately 0.74 inch of water (185 Pa). The energy costs, which depend on average pressure drop, and total costs can also be similar for filters with a wide range of efficiency ratings. Based on the available data, the more efficient filters generally have a higher cost; however, these costs are small on a per person basis. The range in total monthly costs of filtration, relative to no filtration, shown on Figure 4 is approximately \$4 to \$11. With a supply air flow rate per occupant typical of U.S. office buildings, the corresponding filtration cost range is \$0.70 to \$1.80 per person per month, which is insignificant relative to salaries, rent, or health insurance costs.

A few limitations and uncertainties deserve a brief discussion. First, it is not certain that our particle concentration metric -- airborne mass per unit volume -- is the most relevant metric for health. For example, perhaps the airborne cat allergen within particles smaller than 2 μm contributes more to asthma symptoms than an equivalent amount of cat allergen within larger particles. We have used the mass concentration because it is the most common metric, but further research is needed to identify the metrics most relevant for health. Second, this paper did not consider the potential release of pollutants from used filters that have an accumulation of particles removed from the air. The emission of odorous compounds from new and used filters is an area of current research. It is possible that odor emissions from used filters may be determined to be an impetus for replacement of filters more frequently than assumed in our cost analyses. Third, in real buildings indoor particle concentrations, particularly for the larger particles, will often be spatially non-uniform, while the model assumes a uniform concentration. Depending on the situation, average particle concentration decreases could be smaller or larger with a spatially-variable indoor concentration. Finally, our filtration cost calculations were based on the readily available data from three filter suppliers. There is no assurance that these data are representative of the most commonly used filters.

Conclusions

1. Predicted reductions in cat and dust mite allergen concentrations from filtration in HVAC systems range from 20% to 60%. Increasing filter efficiencies above approximately ASHRAE 65% (MERV 11) does not significantly reduce predicted indoor concentrations of cat and dust mite allergen.
2. Relatively large, e.g., 80% decreases in indoor concentrations of ETS and outdoor fine-mode particles are attainable with practical filter efficiencies. Increasing the filter efficiency above ASHRAE 85% (MERV 13) results in only modest predicted incremental decreases in indoor concentrations of these

particles. Filters with an efficiency rating of ASHRAE 45% (MERV 9) or lower are not effective for reducing indoor concentrations of these particles.

3. Energy costs and total costs can also be similar for filters with a wide range of efficiency ratings. Total filtration costs of approximately \$0.70 to \$1.80 per person per month are insignificant relative to salaries, rent, or health insurance costs. More frequent filter replacement, than recommended by manufacturers, could save energy and sometimes also slightly decrease filtration costs.

Acknowledgments

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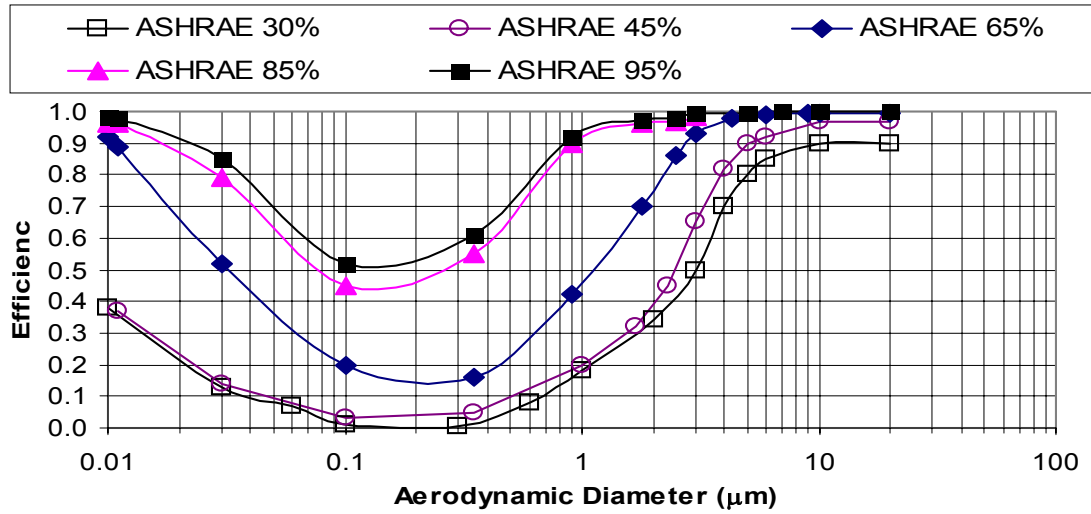


Figure 1. Particle removal efficiencies used in the calculations.

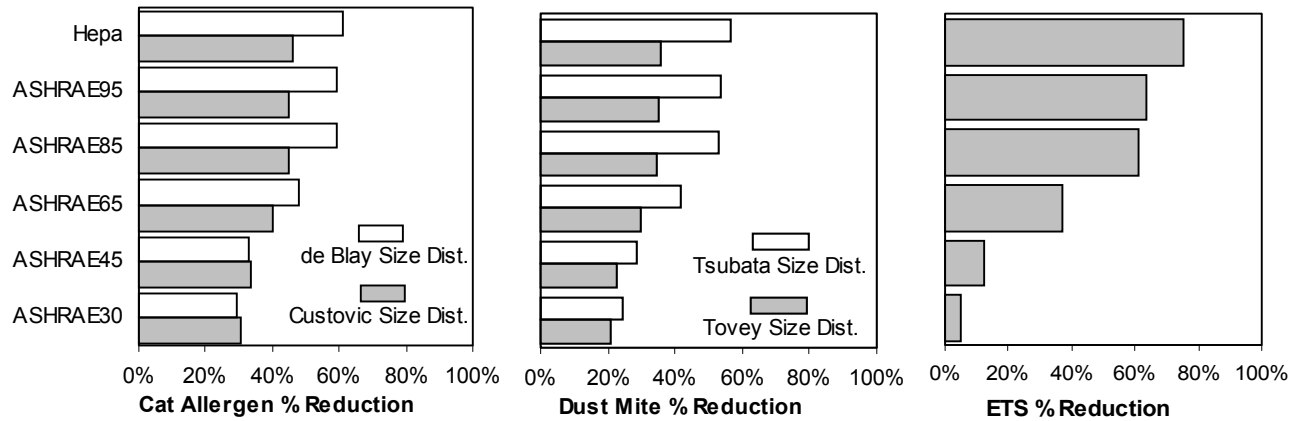


Figure 2. Predicted reductions in indoor concentrations of indoor-generated particles with supply airstream filtration, under the base-case conditions: 1 h^{-1} outside air supply, 4 h^{-1} of recirculation, and 0.25 h^{-1} of unfiltered air infiltration. For cat allergen, calculations were made using particle size distributions from de Blay et al. (1991) and Custovic et al. (1988). For dust mite allergen, calculations were made using particle size distributions from Tsubata et al. (1996) and Tovey et al. (1981).

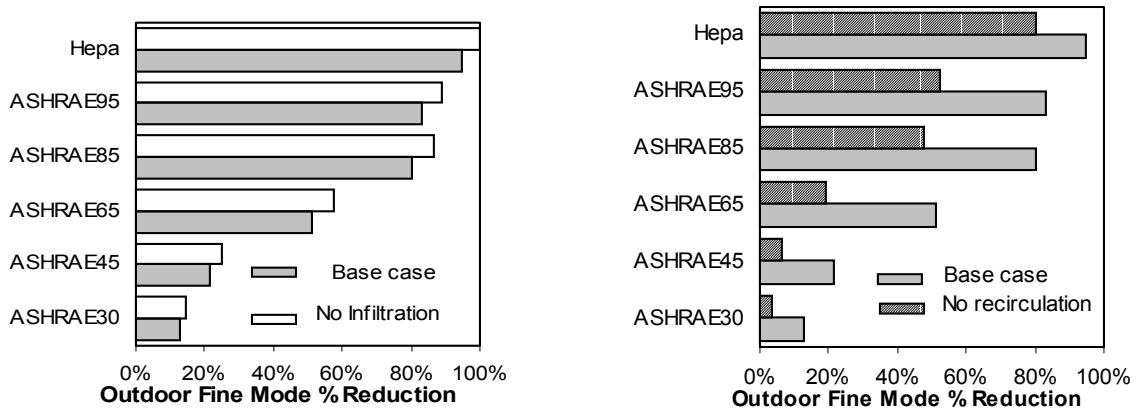


Figure 3. Predicted reductions in indoor concentrations of outdoor fine-mode particles with base case conditions, and with air infiltration or air recirculation eliminated from the base-case conditions.

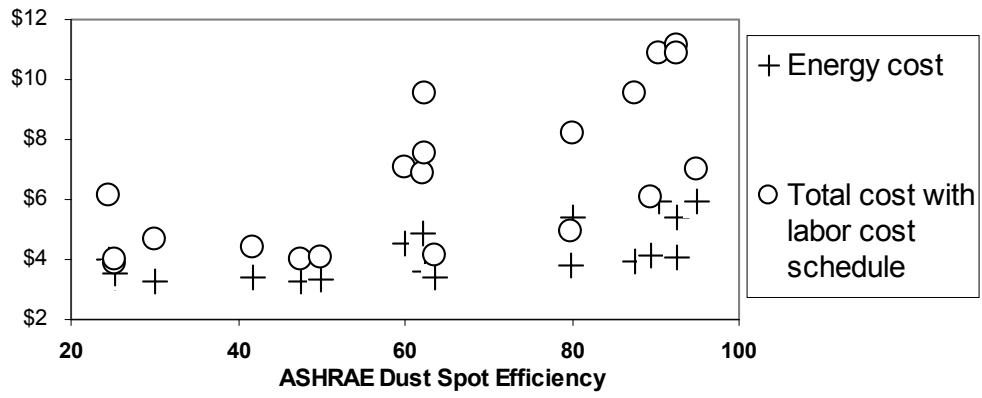


Figure 4. Monthly cost per 1000 ft³ /min (470 L/s) of supply air for filters with different ASHRAE Dust Spot Efficiency ratings. Total costs include the costs of the filters, labor to remove and replace the filters, and fan energy.